DETECTION OF BLURRED CRACKS:
A STEP TOWARDS AN EMPIRICAL VISION STANDARD

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ABSTRACT

There are no government mandated vision standards for aviation maintenance inspectors. Empirically derived vision standards for other occupations cannot be extended to this very different occupation. One important maintenance task is the detection of metal fatigue cracks. To assess the effects of lowered visual capacity on this visual detection task, we measured detection performance by aircraft maintenance inspectors as a function of image blur. The data are used to estimate the effect of blur-induced acuity decline on crack detection probability, and provides empirical support for the construction of a task-relevant visual acuity standard.

INTRODUCTION

It is difficult, if not impossible, to eliminate human error in the process of inspection. Interventions must be developed to reduce these errors and make the process more error-tolerant. Since visual inspection represents a large part of aviation maintenance inspection, one mitigation strategy is to define vision standards for this vision-intensive, safety-critical occupation. A fine-tuned ability to localize, detect, discriminate, and identify job-relevant stimuli can bring cost savings and safety benefits to industry.

In 2001, an FAA Advisory Circular (AC No: 65-31) recommended examination guidelines for the vision of non-destructive inspection (NDI) personnel. It was suggested that near and far vision in at least one eye must be 20/25 and 20/50, respectively. Both near and far requirements could be met with corrected or uncorrected vision. This FAA recommendation was based on acuity standards defined in other NDI/NDT occupations.

No current general standard exists in the aviation industry for the visual qualifications of aircraft maintenance inspectors. Some maintenance facilities use the visual acuity and color vision standards suggested in the FAA Advisory Circular, while other facilities have defined their own vision requirements. This illustrates the need for a uniform and universally accepted set of vision standards that would apply to all aircraft non-destructive inspection and testing (NDI/NDT) personnel.

There are several broad steps that should be taken toward setting an objective and empirically-based occupational vision requirement. The first step is a thorough vision task analysis. In the current context, the FAA commissioned CAMI to perform this analysis focusing on the role of visual processes. Next, to see if a rigorously defined standard can be borrowed from a similar occupation, a review of the literature should be undertaken. Beard *et al.* (2002) compiled a review of a text and WEB-based search for occupational vision requirements, knowledge gained from site visits to major aircraft maintenance facilities, relevant information from technical, mechanical, and inspection textbooks, the FAA maintenance human factors web-site[1][1], and the human vision literature. Beard *et al.* (2002) found no studies that allow generalization of standards to aircraft maintenance inspection. It is unknown how similar tasks must be to validly borrow standards from another occupation without being subject to compromise. What is needed is a rapid, empirically-based methodology for defining occupational vision standards.

If the standard cannot be legitimately borrowed from a previous standard, an objective research methodology should be followed. In their review of the vision standards literature, Beard et al. (2002) identified four occupations that had empirically derived standards. These empirical methodologies ranged from mathematically measuring the size and working distance of the critical visual details (Sheedy, 1980)

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[1][1] http://hfskyway.faa.gov

to psychophysical measurements with blurring lenses placed in front of the eye on a single task (Good & Augsburger, 1987; Good et al., 1996) or multiple tasks (Padgett, 1989).

Here we present a strategy for defining a visual acuity standard that permits increased experimental control by blurring the image before presenting it to the observer, within a computer program. In this way what is done to the signal is exactly known.

The primary objective of this research is to aid in the development of recommendations for visual acuity requirements for aviation inspection personnel. Specifically we determine that visual acuity deficits reduce critical task performance and show in graphical form the relationship between acuity decline and performance.

METHODS

Choice of a critical vision task for inspectors

The central question that must be addressed is "At what level of visual deficit would a maintenance or inspection worker become unable to safely and efficiently perform the critical visual tasks required by the job?" Aircraft inspection is a complex process, requiring many tasks, skills, and procedures. There are multiple critical vision tasks that the workers are required to perform. One purpose of inspection is to detect surface discontinuities such as cracks within the airframe and powerplant regions of the aircraft. Cracks are typically caused by two surfaces being overlaid at a boundary (Hellier, 2001). Since these cracks may be very small and of low contrast, adequate visual acuity is likely to be involved in their detection. After consultation with domain experts, crack detection was chosen as the representative task in order to ultimately set a visual acuity standard for aircraft maintenance inspection.

Psychophysical Experiments

Observers

Two female non-inspection personnel (age range from 23-30) and seven male maintenance inspectors (age range from 35-58 years) participated in the study. Maintenance inspectors were actively employed and had from 10-18 years on the job. All wore corrective lenses, though not always while inspecting. Near and far visual acuity, stereo vision, and color vision tests revealed that all had at least 20/20 acuity, good color vision, however one inspector lacked stereo vision.

Stimuli

Airframe and powerplant crack images were obtained from various sources. Color images were converted to 8 bit black-and-white images to delete any color cues. Before the experiment, "crack removed" stimuli were generated. Using Photoshop^{TM}, the crack was deleted from the image while maintaining the integrity of the background image.

A difference image (the crack alone) was generated by subtracting the no-crack image from the image with the crack. A "background-with-crack" image at contrast level C was generated by multiplying the difference image by a C ($<=1$) and adding it back to the background image. The contrast in dB is $20 \log_{10}C$. An image with a contrast of 0 dB has the original crack. An image with a crack contrast of 6 dB has the difference image reduced by a factor of C = 0.5. This logarithmic scale keeps the variation in the results more constant at different threshold levels.

Crack length estimation

To accurately determine the crack length and width, estimates of the magnification in each photo had to be determined. Each photo included a circular label or 'sticky' whose diameter is a known 0.75 in. To estimate the image magnification, Photoshop^{TM} was used to identify the coordinates of six points along the perimeter of the sticky. These estimates of the perimeter were taken by eye; therefore the error in these judgments was also determined. A computer program took these data and computed a magnification value estimating the diameter of the sticky. When the sticky was on a flat surface, the image is an ellipse and the estimates were very accurate. Some of the stickies were located on an edge or curved surface. In these cases, coordinates were identified only on the flat portion of the sticky and the ellipse estimated based on this flat portion.

Figure 1: Crack length and width estimates. Each image included a circular label or 'sticky' whose diameter is a known 0.75 in. On the left the sticky is located on a flat surface. On the right the sticky is located on a curved surface. A magnification value estimating the diameter of the sticky was computed from six points along the perimeter of the sticky (shown in the figure).

At first, images were adjusted so that all the stickies had a diameter of 0.75-in on the experimental display screen (the actual size), but these images were so coarse because of display resolution limitations that features of the fine cracks disappeared. Images were then adjusted to a screen sticky size of 3-in, resulting in an average image width reduction from 1500 pixels to 800 pixels. Some of the images were still larger than the screen resolution of 1024 by 768 and so were cropped to 990 x 660.

Apparatus

Photographs of large engine airframe cracks were presented on a 1024x758-pixel display screen (SONY Trinitron). Viewing was binocular with natural pupils. From observations of aircraft inspectors performing primary inspections, Good (personal communication) found that the majority of visual observations were done in the distance range from 34 to 40 cm. Because of screen resolution limitations, images were magnified by 4 as discussed above and so the experimental distance was comparably increased to 160 cm. From this distance each pixel subtended 0.31 arc min. The display background screen had a mean luminance of approximately 40 cd/m^2. Three lights illuminated a gray wall behind the monitor. Another lamp illuminated the ceiling behind the observer to achieve ambient lighting. Photometric measurements of the SONY monitor revealed that screen luminance values remained constant only after it was turned on for at least 45 minutes.
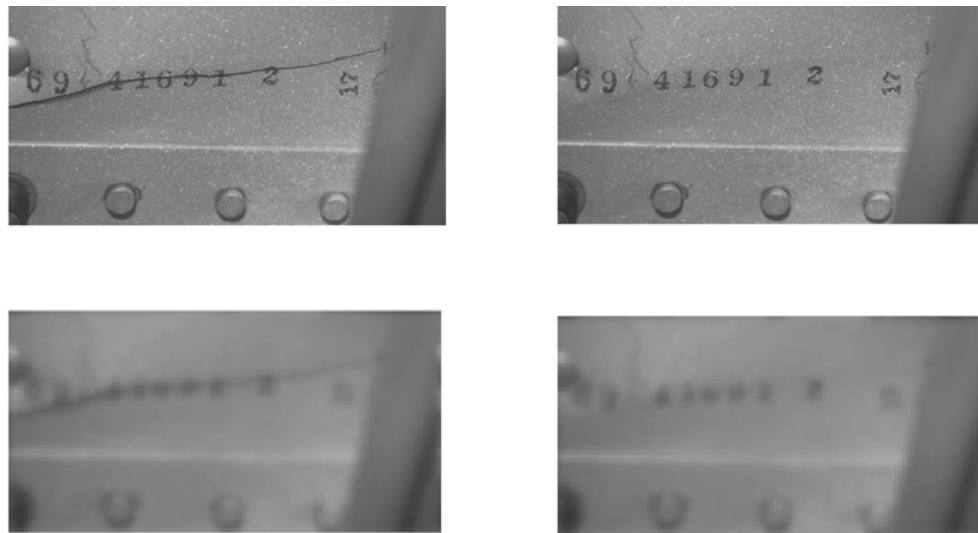

Figure 2: Example of an image with crack (upper left) and without crack (upper right) images. The two lower panels show these images after they have been blurred to simulate lower visual acuity.

Simulating Visual Acuity Decline

Although the shape of the human blur function differs between individuals and changes for different optical conditions, it can be approximated by a Gaussian blur function. An observer with 20/20 visual acuity was

assumed to have a Gaussian blur spread[2[2]] of 2 arc min (Barten, 1999; Ahumada, 1996). A person is said to have 20/40 visual acuity if they see at 20 ft what a 20/20 person sees at 40 feet. If we assume that the 20/40 person has the same contrast sensitivity as the 20/20 person, then the blur for the 20/40 person must be twice the blur of the 20/20 person. Therefore, to simulate 20/40 visual acuity the combined blur of the image and the observer should be 4 arc min. The combination rule for Gaussian blur is the Pythagorean rule, so, for example, to obtain an acuity value of 20/40, the image blur spread was set to 3.46 since the $\sqrt{(3.46^2 + 2^2)}$ is 4. To obtain an acuity of 20/A where A = the desired acuity level, then the blur in minutes $= 2 \sqrt{((A/20)^2 - 1)}$. Figure 2 presents example "crack removed" and background-with-crack images with and without blur.

Procedures

Crack Contrast Detection Thresholds

To increase the number of images tested and the range of conditions, the two non-inspector observers collected data on a large set of crack images at a greater number of blur levels, while the NDI/NDT inspectors were run on subsets of crack images and blur levels.

Contrast detection thresholds were obtained using a two interval forced choice staircase method. The background airframe image remained on during the duration of the block of trials. On a single trial, observers were presented with the background alone in one 0.5 sec time interval and the background with crack in another 0.5 sec time interval. The interval containing the crack was randomized. The two time intervals were demarcated with a simultaneous tone. Interval one contained one tone burst, while interval two contained two tone bursts. Only one of the time intervals contained the crack stimulus. The observer's task was to choose which interval contained the crack stimulus by pressing one of two keys. The inter-stimulus interval was 0.5 sec. The sequence of each block of trials and the crack with background image were randomly chosen.

A different airframe image was presented in each block of trials, selected by a random permutation of all of the images and blur levels to be presented in a replication, for at least three replications. To help the observer find the crack, in initial practice trials the crack position was indicated to the observer by surrounding the crack with a rectangle. After localizing the crack, the observer could then practice the crack detection task without the surrounding rectangle before continuing on to the experiment.

On the first trial of a block of trials, the crack stimulus was presented above threshold. Estimates of these supra-threshold contrast levels were determined from model predictions (see Ahumada & Beard, 1998) and pilot data. The contrast was adjusted by a staircase procedure. On each trial, if the observer correctly responded as to which interval in which the crack was shown, then the response was tallied as correct. After three consecutive correct responses, the crack contrast was decreased by a specified amount (step factor). If the observer chose the interval that did not contain the crack stimulus, then a brief feedback tone would sound, the response was tallied as incorrect, and the crack contrast increased by a specified amount on the next trial. To more rapidly converge to threshold, initially the contrast step factor was 2 dB, but was reduced to 1 dB after a change in the direction of the staircase (a reversal), and then reduced to 0.5 dB after the second reversal. After eight reversals in contrast and at least 30 trials, but no more than 50 trials, the block of trials was terminated and the detection threshold calculated by a probit analysis for that crack with background image.

The two non-inspectors collected data on 10 images. The seven highly experienced aircraft maintenance inspectors collected data on either a subset of these same 10 images or on 5 different images. Observer CA collected data on images at six levels of blur or acuity levels: 20/20, 20/25, 20/30, 20/35, 20/40, and 20/50. Observer KJ saw these acuities plus the acuity level 20/45. The 7 maintenance inspectors collected data on 4 acuity levels: 20/20, 20/30, 20/40, and 20/50. To evaluate the effect of viewing distance on the detection thresholds, one NASA observer was run on a subset of her conditions at a farther viewing distance of 267 cm.

[2[2]] The spread is the distance from the center to where the blur amplitude is 1/e (0.3679) of the center amplitude.

Contrast Sensitivity Functions

To estimate the observer's internal blur and screen resolution limitations, each observer's contrast detection thresholds were measured for a range of stimuli. The Contrast Sensitivity Function (CSF) provides an estimate of visual acuity because an individual's resolving power is indicated by the intersection of the curve on the abscissa of the graph. Horizontal and vertical contrast thresholds were obtained to estimate orientation differences in the amount of blur within the experimental display.

Much like the experimental task, the observer had to decide in which of two 500 msec intervals the stimulus was presented and respond accordingly (i.e., they responded by pressing '1' if they thought the stimulus was presented in interval one, and '2' if they thought the stimulus was presented in interval two.) There was a 300 msec gap between the presentations of the two stimulus images. Instead of cracks, however, the target stimuli for this experiment were a square, a line and a dipole. Observers completed this experiment while sitting at a distance of 273 cm from the screen.

RESULTS

Probit analyses were done on each block of trials to estimate the contrast threshold, the value at which the probability of correctly identifying the interval was 75%. The median of the scores replicating a particular condition was then computed. In Figure 3, detection thresholds are presented across blur or simulated acuity levels. Each symbol represents a different airframe image.
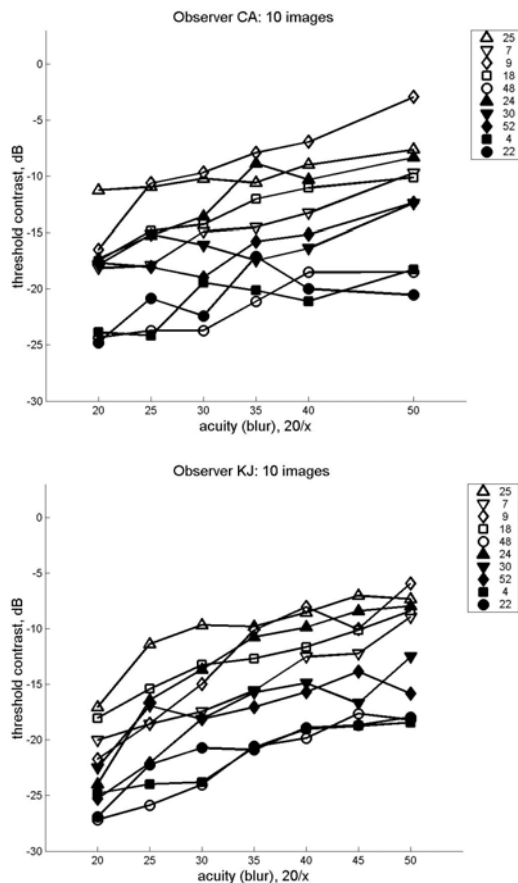

Figure 3: Contrast thresholds are presented across blur or simulated acuity levels. Each symbol represents a different airframe image. The results for observers CA and KJ are shown.

Figure 4 presents contrast thresholds for the different images as a function of blur averaged over the four inspectors of group 1 and two of three inspectors in group 2. The data of one inspector in group 2 was not included because he was unable to see the cracks at the higher blur levels. Each symbol represents a

different airframe crack. The effect of blur tends to be larger for cracks with higher thresholds. The two images with the highest thresholds could not be run at the higher blur levels
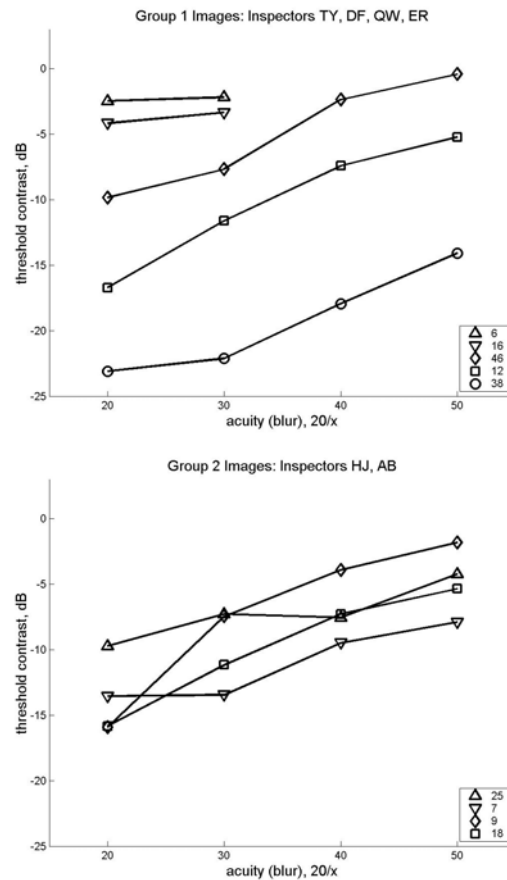

Figure 4: Contrast thresholds for the different images as a function of blur averaged over inspectors. Each symbol represents a different airframe image.

Figure 5 shows the effects of blur on observers averaged over images. Data for images that were visible for all blur levels are shown. The effect of blur is quite consistent over inspectors. The two non-inspectors (CA and KJ) showed lower detection thresholds than did the experienced aircraft inspectors. A likely reason is that the non-inspectors had participated in a study of practice effects on contrast thresholds using similar images (Beard, et al., in preparation).
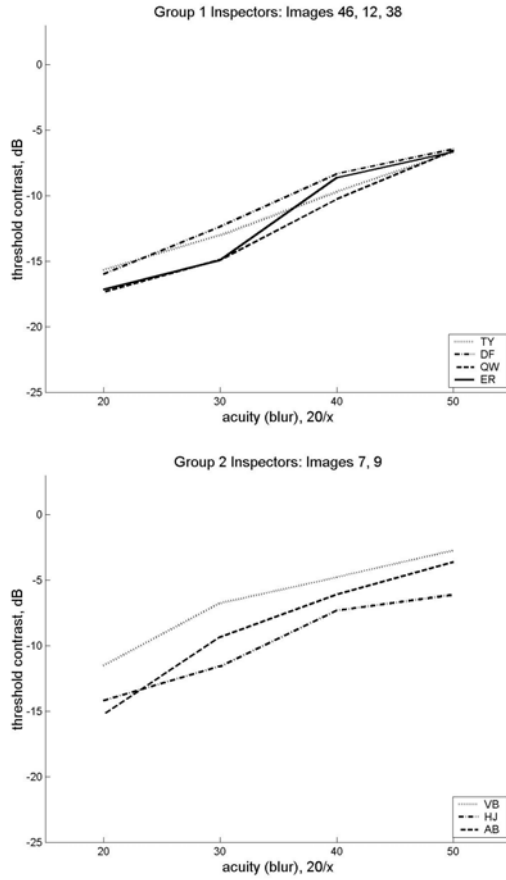
Figure 5: Effects of blur for each observer averaged over images. Observer initials are shown in the legend.

All data presented thus far were collected at a distance of 160 cm. Because all inspections are not done from one single distance, thresholds were measured from a second distance of 266.8 cm. Thresholds were elevated at the further distance, but show a similar increase in threshold with increases in blur.

Figure 6 shows the effect of increasing the viewing distance. Thresholds for the far distance are consistently higher than those for the nearer distance. If the detection were simply a function of target contrast energy, the threshold would be expected to increase by $20 \log_{10}(267/160) = 4.4$ dB.   Attenuation of the high spatial frequency energy should cause an additional increase in the threshold, which should be greater for the less blurred stimuli and the higher threshold stimuli.
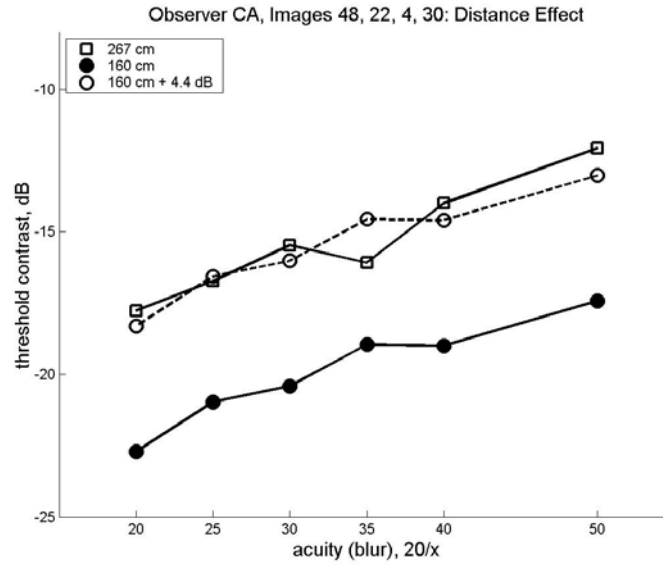
Figure 6: Viewing distance effect for observer CA. The effect can be predicted by the effect of magnification on contrast energy without considering spatial frequency effects.

To foster translation of these data into an occupational visual acuity standard, in Figure 7 we have transformed the data from Figure 4 into Probability of Detection (PoD) curves. The data were converted back to probability of Yes/No detection after being normalized by setting the probability of detection for 20/20 to 0.99 or 0.90. This calculation depends strongly on the assumed slope of the psychometric function. Here we assume the standard deviation of the cumulative Gaussian is 4 dB, but the actual value could be anywhere from 1 dB to 6 dB.
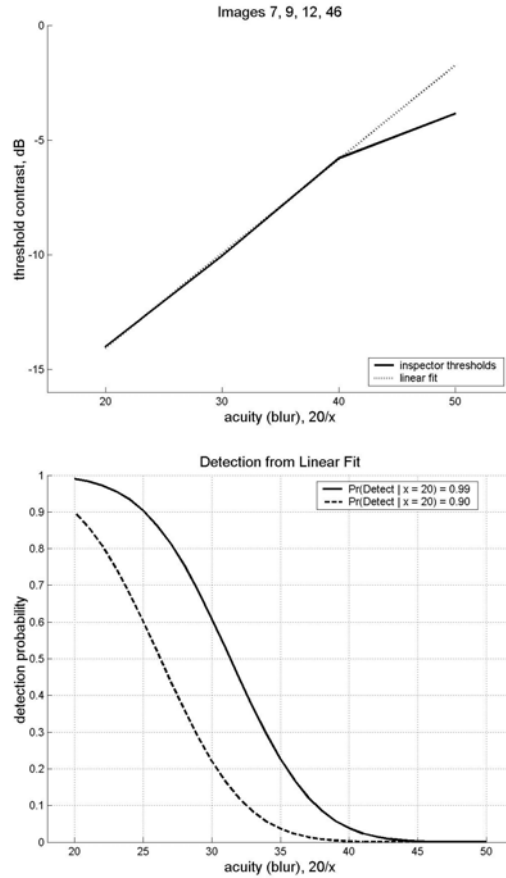
Figure 7: Average data from Figure 4 and a linear fit to that data (left). Probability of Detection curves based on the linear fit (right). The probability of a correct response at 20/20 was arbitrarily either set to 0.99 or 0.90.

DISCUSSION

Although good vision is a vital qualification for aircraft maintenance inspectors, no general standards for visual acuity currently exist for this occupation. Vision standards from other occupations cannot be "borrowed" to set a standard for maintenance inspectors because the visual demands between occupations are dissimilar and the majority of occupational vision standards are not empirically based (Beard et al., 2002).

One way to look at the effect of not having 20/20 vision is to say that an inspector with 20/40 vision sees at 20 feet what the 20/20 inspector sees at 40 feet. That is to say that the 20/40 inspector has to be twice as close as the 20/20 inspector to make the same discriminations. When the viewing distance is halved, the foveal search area is reduced by a factor of 0.25, so it would take about 4 times as much time to search the same area with the same discriminative ability if there is an acuity deficit to 20/40.

In this project we measured detection performance on a representative task performed by aircraft maintenance inspectors as a function of image blur. These measurements allow predictions of the amount the probability of detection could change as a function of blur. As shown in Figure 7, cracks whose detection was initially at 99% could be greatly reduced by blur corresponding to only 20/30 if the inspection situation was kept constant in all other respects.

The amount of visible contrast energy in the crack correlated well with the contrast thresholds for the crack (r = -0.89). However, the effect of the blurring on the thresholds was much greater than the loss in visible contrast energy. For the two images with the greatest loss in visible contrast energy (4.7 dB) at the 20/40

blur level, the average threshold loss was 10 dB. Although this may be in part due to a lack of experience with these blurred images, it is also possible that the blur causes more problems with crack detection than predicted by contrast energy loss alone, such as affecting the extraction of edges. The loss in visible contrast energy can be thought of as a lower limit for the effect of blurring.

Blurring is only one possible cause of lowered acuity. Another possible cause is decreased overall contrast sensitivity. In this case, the predicted effects are expected to follow more closely the rule that cutting the viewing distance in half will compensate for a 6 dB loss in sensitivity.

Methodological Limitations and Strengths

The experimental image generation procedure was only an approximation of actual visual inspection. Inspectors were able to use only one very relevant strategy (contrast detection) to look for the defect embedded within a number of realistic aircraft locations. Although the cracks were positioned on actual aircraft structures, inspectors could not use many of the common strategies used in their work environment, such as tribal knowledge (knowing where to look), moving closer, use of shadows (i.e., changing the angle of light from their flashlight), touching the crack. But there is a trade-off between being able to use these techniques and the time it takes to do a search.

Differences between the background conditions indicate the effect of background variations on performance and will reduce the importance of decision strategies on defect detection. This methodology permits manipulation of defect absence, length, color, and other attributes. It is important to be capable of manipulating the absence of a defect since uncertainty plays a large role in maintenance inspection (i.e., there is no prior knowledge that a defect will be present). In fact, it is only occasionally that a defect is actually present.

Vision is a fundamental component of effective aircraft inspection. All the same, so too are other cognitive factors such as attention, memory, and experience. Inspectors are knowledgeable about individual components as well as the overall aircraft being inspected, thus they possess the background to properly locate, identify, and evaluate aircraft defects. Often NTSB accident reports will point at visual deficits as contributors to accidents because a crack went undetected, or a worker failed to detect fatigue damage. However, it may not be that vision led to these overlooks. Other cognitive factors may have played major roles in the lack of detection: job-related stress, worker fatigue, multi-tasking, or memory effects of interruptions. The proposed research isolates vision requirements on these duties. Because the job entails much more than vision, these results may not relate to how well the inspector will do on the job. Therefore, although vision is a critical component in inspection, other factors weigh in heavily in the naturalistic task.

Other requirements should address the effects of other cognitive contributors. These data can then be used by the FAA to write acceptable cognitive and perceptual standards and procedures for inspectors including the type and frequency of vision testing necessary to ensure the safe and effective performance of current employees and job applicants who will perform a particular inspection procedure.

Although psychophysical human-in-the-loop experiments can provide accurate and objective data toward setting a standard, it would be optimal to be able to predict performance using a computational model. Ahumada, Beard, & Jones (2005) show that a model of image discrimination does predict similar blur effects as reported for model predictions of simulated crack stimuli (Beard et al., 2003) but under-predicts the blur effects seen in psychophysical data using these actual crack stimuli.

Guidance toward the setting of a standard

These measurements do not provide a standard, but it converts the problem to specifying a desired physical limitation in performance. The final step in the process of defining a visual acuity standard lies in the hands of the FAA. Using the data in Figure 7, the FAA must decide which stimulus characteristics and what margin of error (e.g., 1 error in one million) will define where to draw the line for the standard.

Recruitment, testing, selection, and training costs are high. The rejection of qualified persons imposes an unnecessary cost on maintenance facilities. While the failure of proper performance on visual tasks could be catastrophic, persons with refractive errors such as correctable myopia who can perform the job should be permitted to do so. Vision requirements should be based on a demonstration that, for example, 20/25 near or 20/50 distance visual acuity is actually needed to perform the essential task. If the task is not generally performed alone (i.e., there are several people in close proximity who provide assistance) then these tasks should not be imposed with a vision requirement for all the individuals. In addition, vision

requirements must be based on tasks that cannot be modified by current available technology to assist the vision of the worker.

The governing body, here the FAA, should clearly define the purpose of any vision test and not provide medical examiners considerable latitude when conducting visual acuity testing and evaluation. An interesting case where this was not done, highlights the importance of this recommendation. In a Safety Advisory entitled 'Determination of Vision Impairment among Locomotive Engineers" (SA-98-1) published by the Federal Railroad Administration (FRA) and the Department of Transportation (DOT), a lesson can be learned for the current purpose. The FRA's expectation was that the physicians who would be designated as railroad medical examiners would be trained to competently administer color vision examinations. Thus, they did not anticipate that it would be necessary to specify for the medical examiners the test procedure to be employed when testing for whether a person meets the standards specified in this rule. That assumption has been called into question under tragic circumstances. If the current rule had been implemented as the FRA expected, the rule would have been adequate to prevent a major railway accident involving the fatal collision between two New Jersey transit commuter trains (NTSB/RAR-97/01). The NTSB report found that the medical history of the suspect engineer showed that he had been administered an acceptable test annually by the same contract physician for over 10 years. In the tenth year, the test results showed a deterioration of the engineer's ability to distinguish among some colors. The engineer was then given a Dvorine Nomenclature Test to further evaluate his color vision. Many color weak individuals can identify the names of colors by their brightness instead of their hue. The examiner failed to administer the accompanying Dvorine Second edition color vision test, which measures color discrimination abilities and therefore the results of the first test suggested that the engineer did not have a problem. It was ruled likely that the accident was preventable if the physician had used a sound approach to measure the person's ability to distinguish colors.

Self-monitoring

Aircraft maintenance inspectors as a group take great pride in their ability to detect defects. In addition, they care deeply about the safety implications of their job. Many environmental and developmental variables can affect visual sensitivity. Changes in vision are typically slow and subtle and therefore not easily identified by the individual. Long work shifts or age-related accommodative changes can lead to eye strain, headaches, excessive rubbing of the eyes, esotropia or exotropia, and reduced efficiency on the job. Without an objective measuring tool, workers will not detect gradual changes in their vision. If you don't see something, you don't know that you can't see it (self-awareness). Providing the workers with a method to self-monitor their visual acuity would enhance occupational safety and safety in the NAS.

The Use of Colored Lenses

In the workplace, some maintenance inspectors wear corrective lenses that have been tinted with a color. Typically, this color is yellow. The media of the human eye bends the light of the spectrum differentially, depending on the wavelength. Yellow light is focused on the retina, whereas blue light is typically several diopters out of focus. This is referred to as lateral chromatic aberration. By filtering out blue light with the use of yellow tinted lenses, images will be more in focus (Wolffsohn, et al., 2000). One might suspect that yellow tinted lenses are a benefit to the wearer. This is not always the case (Tredici, 2005). Unless the colored lens is of unusually high quality, the amount of light reaching the eye is reduced, even though the perceptual experience while wearing yellow tinted lenses suggests that the environment appears brighter (Kelly, 1990). Therefore, in terms of visual acuity, there is a trade-off between the reduction in the amount of blue light reaching the retina and the lower yellow light level produced by the filtering lens. Workers who feel they benefit from such lenses might consider using an LED flashlight where the blue LED could be turned off. There would then be no loss or scattering of light by lenses.

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